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Review & Analysis

Automation Effects on a Driver's Vigilance in the Automated Highway System, Volume I. Final Report.

Prepared for: MONTEREY TECHNOLOGIES, INC.
987 UNIVERSITY AVENUE, SUITE 12
LOS GATOS, CA 95030

JOYCE A. CAMERON
HUMAN FACTORS ANALYST

ANTHONY J. SOTTILE
HUMAN FACTORS ANALYST

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Joyce A. Cameron Anthony J. Sottile

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CSERIAC Program Office
AL/CFH/CSERIAC Bldg 248
2255 H Street
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NOTICE

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ABSTRACT

ABSTRACT

The Automated Highway System is part of efforts to introduce high levels of automation into motor vehicles. Anticipated benefits of this automation include improved highway safety and increased highway capacity. Operator vigilance is essential in highly automated environments such as cockpits and nuclear power plant control rooms. Increased vehicle automation may also require increased driver vigilance. Results of laboratory vigilance studies suggests that human performance on vigilance tasks decreases over time. Results of operational vigilance studies indicate that there may be an interaction between vigilance performance and the minimum level of acceptable task performance. In some situations a vigilance decrement may be operationally significant; in others it may be operationally insignificant. In addition, lessons learned from experience with high levels of automation in other environments directs attention to the importance of operator mental workload and situation awareness.

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ACRONYMS AND ABBREVIATIONS

AHS	Automated Highway System
CSERIAC	Crew System Ergonomics Information Analysis Center
GIDS	Generic Intelligent Driver Support
ITS	Intelligent Transportation System
IVHS	Intelligent Vehicle Highway System
NASA-TLX	National Aeronautics and Space Administration-Task Load Index
SA	Situation awareness

1. INTRODUCTION

1.1 Purpose

The Automated Highway System (AHS) is part of efforts to introduce high levels of automation into motor vehicles. Anticipated benefits include improved highway safety and increased highway capacity. Efforts to increase vehicle automation, if carried to their logical conclusion, could lead to complete automation of the driving task, and to a profound change in the driver's role—from actor to monitor.

Successful monitoring requires vigilance, and information about human vigilance performance is needed to support initial decisions concerning the driver's role. Should the driver's task in the AHS be vigilance monitoring of high levels of automation, or not? To address this issue, Monterey Technologies, Inc. (Los Gatos, CA) tasked the Crew System Ergonomics Information Analysis Center (CSERIAC) with preparing a *Review and Analysis*. Of special interest is information about human capabilities in the areas of vigilance and signal, or target, detection. Also of interest is information about changes in man-machine roles in other highly automated environments, and about human factors issues related to such automation.

1.2 Assumptions

Operator vigilance is essential in highly automated environments such as cockpits and nuclear power plant control rooms. It is assumed that the high levels of automation associated with current concepts of the AHS will also require vigilant operators (*i.e.,* "drivers"). However, operator vigilance, and the related issues of mental workload and situation awareness, are one kind of issue raised by experience with high levels of automation in other complex systems.

A second kind of issue is the relationship between responsibility and authority. It is one thing when the person who is responsible has the authority to take action; it is another when the person who is responsible does not have the authority to act because of constraints imposed by automation. Detailed discussion of this issue is beyond the scope of this study. Nevertheless, it must be recognized that as automation increases, the driver's authority may be decreased while the driver's responsibility may remain unchanged, and this situation will lead to complex legal issues.

Three assumptions have guided CSERIAC's literature search. First, the focus is on basic human factors data and information about human abilities and capabilities that can support decision making concerning the driver's role in AHS. Second, the primary literature of interest concerns vigilance and signal, or target, detection, but other relevant issues should be addressed. And, third, the customer is very familiar with literature directly related to Intelligent Vehicle Highway Systems (IVHS) and Intelligent Transportation Systems (ITS). These assumptions were used to develop the search strategy, edit the results of the literature search, and identify pertinent citations documented in this report.

1.3 Overview

Vigilance is the issue of primary concern in this *Review and Analysis*, and key findings related to vigilance are presented in Section 3.2. Even more basic issues—the nature of the driving task and the characteristics of drivers—are described in Section 3.1. Information about workload and situation awareness derived from experience with high levels of automation in other complex systems is provided in Section 3.3. In addition, three studies that relate vigilance and driving are described in Section 3.4.

To prepare this study, CSERIAC conducted an extensive search of government and commercial databases for literature related to vigilance, signal detection, driver abilities and capabilities, automation, and the Automated Highway System. The search strategies associated with the results from each database indicate the depth and breadth of the search. In addition, CSERIAC analysts consulted sources found in our in-house collection of human engineering-related textbooks, handbooks, design guides, standards, and journals.

The on-line search for bibliographic information regarding *Automation Effects on Driver Vigilance in the Automated Highway System* contains citations and abstracts from non-copyrighted and copyrighted databases. Three non-copyrighted databases were searched, and the search results are contained in Volume II:

- Defense Technical Information Center (DTIC) Technical Reports (TR)
- DTIC CD-ROM
- DTIC Work Unit Information Summaries (WUIS)

Ten copyrighted databases were searched, and the results are presented in Volume III:

- Dissertation Abstracts Online
- Engineering Information, Inc. Compendex (Ei Compendex *Plus™)
- Energy Science and Technology
- Information Services for Physics, Electronics, and Computing (INSPEC)
- National Aeronautics and Space Administration Remote Control (NASA Recon)
- National Technical Information Service (NTIS)
- PsychINFO®
- Science Citation Index Search (SciSearch®)
- Society of Automotive Engineers (SAE)
- Transportation Research Information Service (TRIS)

To support further research, three types of resources are provided. Appendix A in Volume I furnishes a list of relevant Internet addresses. Volume II, *Non-copyrighted Literature Search Results,* and Volume III, *Copyrighted Literature Search Results* contain the results of database searches and listings of especially interesting documents.

The initial on-line database search revealed approximately 650 citations and abstracts, some of which were unrelated to the objectives of this report. Irrelevant citations were eliminated from the search results presented in Volumes II and III. Insofar as possible, we have removed duplicates from these literature search results. However, we have not removed citations and abstracts for references cited in Volume I, because they may contain useful information.

2. APPROACH

The information included in this study comes from two major traditions in human factors research: (1) studies conducted using carefully controlled experiments, and (2) studies conducted in real or simulated operational environments. The majority of the information about vigilance comes from highly controlled experimental studies. The results of these studies contribute to an "idealized" conception of vigilance performance on controlled tasks where the purpose is to gain information about vigilance task performance by consciously varying characteristics of the signal, the task environments, or the human performance. The few studies of vigilance that have been conducted in operational environments are of special interest in light of the assumed "real world" driving task.

3. FINDINGS

The findings are structured in four main sections. Section 3.1 provides information about driving and drivers. Section 3.2 reviews some key findings about vigilance in experimental and operational settings. Section 3.3 examines some of the human factors issues raised by experience with high levels of automation in other operational environments, and focuses on issues related to mental workload and situation awareness. Section 3.4 reviews a few studies that address driving and vigilance, driving and mental workload, and driving and situation awareness.

3.1 Driving and Drivers

3.1.1 The Driving Task

When driving, the driver must perform three essential functions: "(a) vehicle control; (b) navigation; and (c) collision avoidance" (Hancock & Parasuraman, 1992, p. 185).[1] Under normal driving conditions, the demands of driving do not generally exceed the human capacity for attention due to the automatization of numerous component tasks through extensive practice (Hancock & Parasuraman, 1992). However, there is evidence that in some situations (*e.g.*, high density traffic or driving through intersections/traffic circles), the demands for attention may exceed human capabilities (Hancock, Wulf, Thom, & Fassnacht, 1990, cited in Hancock & Parasuraman, 1992).

In addition, driving may occur at any hour of the day, and it has been characterized as "a good example of a real-world *divided* attention task" (Hancock & Parasuraman, 1992, p. 185). A brief, high-level task analysis of driving shows that it currently includes a variety of monitoring tasks including monitoring the condition of the vehicle, the conditions outside of the vehicle, and the conditions inside of the vehicle. Monitoring the *condition of the vehicle* typically involves parameters such as speed, fuel, and engine temperature. Monitoring the *conditions outside of the vehicle* can include factors such as traffic flow, highway condition, and weather; monitoring *the conditions inside of the vehicle* may focus on the activities of passengers, especially young children. In addition, a driver may simultaneously engage in other tasks such as listening to music, talking to passengers, eating, drinking, or using a cellular phone, all while attempting to navigate from point A to point B without mishap.

3.1.2 The Driving Population

The driving population is highly diverse. In fact it "is probably one of the broadest of all consumer user populations, at least in the developed countries where almost everyone rides in cars" (Peacock, 1993, p. 473). New drivers are frequently in their teens; long-term drivers may have experienced some deterioration of sensory and cognitive abilities. In addition, there is tremendous variation in driver knowledge, skills, and experience, and in driver size, strength, and health. According to Peacock (1993), the challenge "is to articulate the interactions between human performance variability and feature complexity in the context of the time constraints

---

[1] Verwey (1990) suggests a second tripartite analysis of the driving task. He writes, "It has become good practice to distinguish three levels in the driving task (e.g., Janssen, 1979). The control level is concerned with elementary vehicle handling functions like lane-keeping and handling of the controls. The manoeuvring level deals with aspects that have to do with car manoeuvring, overtaking, intersection negotiation and the like. Finally, the strategical level regards route planning and following" (p. 18).

imposed by driving. . . . The future of road transportation will change, but the nature of human behavior and traffic will be more resistant to change" (pp. 475-477).

3.1.3 Possible Roles for Drivers in the Automated Highway System

Traditionally, the driver's role in highway transportation has included vehicle control, navigation, and collision avoidance. Today, technology is available to aid the driver in vehicle control (*e.g.,* intelligent cruise control), navigation (*e.g.,* in-vehicle navigation systems and a variety of traffic management systems), and collision avoidance (*e.g.,* front, side, and blind spot detection devices, Intelligent Transportation System [ITS] America, 1995). The driver's tasks may have changed for those who use these aids, but the driver's basic role has not. He or she is still responsible for performing the essential functions of vehicle control, navigation, and collision avoidance.

The driver's role in the Automated Highway System has not yet been determined. According to Michael McCauley, there are several possible roles/responsibilities for the driver in the AHS. Three of these possibilities are shown in Figure 1.

1. Monitor the outside environment to supplement/assist an immature collision detection & avoidance system (watch for deer) 2. Monitor the proper functioning of automated vehicle control 3. Relax until the system gives an 'alert'; then standby to resume manual control	Increasing Automation ↓

Based on personal communication from Michael McCauley (17 March, 97).

FIGURE 1. **Possible AHS driver roles under increasing automation.**

In the first possibility, the human is assigned the role of monitor, and his/her tasks are likely to require sustained attention and vigilance. However, the nature of the human response required when a signal is detected is not yet clear (personal communication, Michael McCauley, 26 March 97). In the second possibility, the human is assigned a role comparable to that of the supervisor of a highly automated industrial process or plant. His/her tasks could be characterized by the term *supervisory control* (*i.e.,* the human operator supervises the automated activity and engages in actual control activities only occasionally). In the third possibility, the human's role is essentially that of a passenger who may have little or no responsibility as long as the AHS is in control, but who must be able to resume manual control when instructed to do so. "This 'no hands' thrust . . . represents essentially the complete automation of driving" (Hancock & Parasuraman, 1992, p. 182). These three possible roles raise important human factors questions related to workload, and especially to the management of transitions in workload as a person resumes manual control (see Section 3.3.2.1 below).

3.2 Vigilance

According to Huey and Wickens (1993), "vigilance or sustained attention refers to the ability of observers to maintain their focus of attention and to remain alert to stimuli for prolonged periods of time" (p. 139). Vigilance was initially studied in conjunction with performance decrements observed in airborne radar observers during World War II. With the increasing pervasiveness of automation, vigilance has become an important component "of

human performance in a wide variety of activities including industrial quality control, robotic manufacturing, air traffic control, nuclear power plant operations, long distance driving, and the monitoring of life signs in medical settings" (Huey & Wickens, 1993, p. 141).

The first systematic laboratory studies of vigilance were conducted by Mackworth (1948, 1961/1950, cited in Huey & Wickens, 1993) who showed, as had been expected from field experience, that vigilance decreases over time, and that this decrease is detectable in a rather short period of time. This decrease, the *vigilance decrement* or *decrement function,* "is the most ubiquitous finding in vigilance studies" (Huey & Wickens, 1993, p. 140). In demanding circumstances, a decrement can be detected within a few minutes of beginning a task (Jerison, 1963, cited in Huey & Wickens, 1993; also shown later in Nuechterlein, Parasuraman, & Jiang, 1983, cited in Huey and Wickens, 1993). In many tasks, at least half the decrement occurs within the first 15 minutes of task performance (Teichner, 1974, cited in Huey and Wickens, 1993).

A key design feature of many vigilance experiments is that the operator knows exactly what "signal" to look for, and exactly what "response" to make when a signal is detected. The development of signal detection theory enlarged the understanding of vigilance and showed that vigilance is not simply a perceptual phenomenon (see Section 3.2.1). Using methods of experimental psychology, supplemented by insights derived from signal detection theory, researchers have investigated the effects of a variety of variables on vigilance performance (see Sections 3.2.2, 3.2.3, and 3.2.4). Attempts to apply the results of laboratory vigilance research to problems in the real world, have led to criticisms of this research on a number of grounds (see Section 3.2.5). And, insights from the few vigilance studies conducted in operational environments have underscored the complex interaction between the nature of the task and the presence, or absence, of the vigilance decrement (see Section 3.2.6).

3.2.1 Signal Detection Theory and the Study of Vigilance

Signal detection theory provides a useful framework for understanding some of the complexity of vigilance tasks because it directs attention to the fact that a detection task involves both sensory evidence of a potential "signal" (*sensitivity* or d' in signal detection terminology) and a decision about whether or not the sensory evidence constitutes the "signal" of interest (*response bias* or β in signal detection terminology). *Sensitivity*, or the observer's keenness of perception, can be influenced by properties of the signal (*e.g.,* intensity, salience) and by characteristics of the human observer (*e.g.,* visual or auditory acuity). *Response bias*, or the observer's tendency to make conservative or risky decisions about the presence of a signal, is influenced by changes in the probability of a signal and by changes in the consequences of one's response (*i.e.,* the reward for correct responses can influence one's response tendencies) (Wickens, 1992).

The data from a signal detection experiment is frequently displayed in terms of four categories—"*hit*," "*miss*," "*false alarm*," and "*correct rejection*." These categories represent a combination of the two states of the world, the signal is present or absent, and the two decision outcomes, the human observer believes the signal is present or absent (see Figure 2).

		State of the World	
		Signal is Present	*Signal is Absent*
Decision Outcome	*Signal is Present*	"Hit"	"False Alarm" False Positives
	Signal is Absent	"Miss" False Negatives	"Correct Rejection"

FIGURE 2. **Four Possible Signal Detection Outcomes** (Based on Wickens, 1992).

Signal detection theory is commonly applied in vigilance studies, and Wickens (1992) has identified two different types of vigilance paradigms: *free response* and *inspection.*

> The *free-response* paradigm, such as that confronting the power plant monitor, is one in which a target event may occur at any time and nonevents are not defined. . . . The *inspection* paradigm, the quality control inspector's task, is one in which events occur at fairly regular intervals. A few of these are targets (defects), but most are nontargets (normal items) (Wickens, 1992, p. 41).

When discussing the use of signal detection in vigilance studies, Wickens (1992) recommends caution, especially when there are few false alarms. Boff and Lincoln (1988) note that many vigilance experiments do not meet the assumptions about normal distributions and equality of variance that underlie signal detection theory, and they indicate that alternatives to d' and β have been developed. A recent article by See, Warm, Dember, and Howe (1997) provides some recommendations concerning the choice of measures of sensitivity and response bias in vigilance experiments.

3.2.2 Human Variables

The *Engineering Data Compendium* (Boff & Lincoln, 1988) includes information about research paradigms that have been used to study vigilance, and data about variables that have been employed in these studies. It includes data about human characteristics and experiences (*e.g.,* age, gender, intelligence, personality, reaction time, boredom), and about the effects of practice, instruction, and training methods on vigilance performance.[2]

In the context of vigilance performance, reaction time is probably the most studied human variable. Boff and Lincoln (1988, p. 1506) indicate that three types of response patterns are consistent across different experimental conditions:

[2] The *Engineering Data Compendium* (Boff & Lincoln, 1988) also provides data concerning the nature of the vigilance task, the vigilance decrement, the characteristics of the signal that affect vigilance performance, the aspects of signal presentation that influence vigilance performance, and the relationship between vigilance and signal detection theory.

1. false alarms (incorrect 'yes' responses) are always slower than hits (correct 'yes' responses), misses (incorrect 'no' responses), and correct rejections (correct 'no' responses);
2. positive responses (hits and false alarms) become slower as time on task increases (i.e., observers take longer to report a 'yes' response); and
3. negative responses (misses and correct rejections) become faster as time on task increases (i.e., observers are quicker to report a 'no' response).

The effects of other human variables on vigilance performance are somewhat inconsistent and have generally been assessed in the context of efforts to identify individuals who would be good at performing vigilance tasks (Boff & Lincoln, 1988). Nevertheless, it is clear that "in most vigilance tasks and vigilance experiments, there is a wide range of variation in performance between individual observers" (Boff & Lincoln, 1988, p. 1528).

The absence of detailed information about human variables in vigilance performance does not imply that these variables are unimportant. Rather, it suggests that they have not been widely investigated in the context of vigilance performance. However, there are a few studies that provide potentially useful data, especially as it relates to the effects of age on vigilance performance.

For example, Surwillo and Quilter (1964), in a study entitled *Vigilance, Age, and Response-Time*, used the Mackworth "clock task"[3] and found that

> the old *Ss*[mean age = 71.0 years] were as vigilant as the young [mean age = 43.7 years] in the initial stages of 'watchkeeping' but, after 45 min. on the task, vigilance declined to a significantly lower level in the older group. However, it should be noted that the percentage success in detecting the 'double jumps' in the 'clock task' was considerably below 100%. The mean percentage detected by the young group was 72.9%, while the corresponding value for the old group was 64.4%. The difference of 8.5% was statistically significant (t-2,21; $P < 0.05$), and we may conclude that, under the conditions of this experiment, old people were less vigilant than young people (p. 617).

In addition, age and aging have been investigated in other contexts including driving and dual task performance. Stelmach and Nahom (1993) reviewed the effects of aging on driving performance and concluded that "motor performance is generally slowed as age advances" (Stelmach & Nahom, 1993, p. 231)[4]. McDowd, Vercruyssen, and Birren (1991) reviewed

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[3] According to Surwillo and Quilter (1964),

> "The 'clock' was a metal box with a plain white face, 12 in. in diameter, and a single black pointer, 6 in. in length, mounted from its center. This pointer moved in discrete steps like the second hand of a large clock. The full circle contained 100 steps, each of which occurred once every second. No reference-points or scale-markings of any kind appeared on the white background behind the pointer. At long and irregular intervals, the pointer travelled through twice the usual distance in the same amount of time. These movements were referred to as 'double jumps' and, in the course of the 1-hr. test, 23 were presented. Since this corresponded to 23/3,600 or 0.64% of all the pointer movements, a double jump was a rare event indeed" (p. 615; based on Mackworth 1948, 1950).

[4] A special issue of *Human Factors,* includes several articles specifically about driving and aging including: *Attention and Driving Skills in Aging and Alzheimer's Disease* (Parasuraman & Nestor, 1991) and *Divided Attention in Experienced Young and Older Drivers: Lane Tracking and Visual Analysis in a Dynamic Driving Simulator* (Brouwer, Waterink, Van Wolffelaar, & Rothengatter, 1991).

research concerning aging, divided attention, and dual-task performance and concluded, "the picture with regard to aging, divided attention, and dual-task performance is a complicated one, but it may be safe to say that in all but the simplest tasks, older adults perform less well under dual-task conditions than do young adults" (p. 405).

3.2.3 Psychophysical Determinants: A Functional Equation

Performance in vigilance tasks is influenced by a variety of stimulus characteristics. One way of organizing these influences is through the "empirically determined functional equation developed by Jerison (1959b) and modified by Warm and Berch (1985), which takes the following form: $P = f(M, S, U, B, C)$" (Huey & Wickens, 1993, p. 142). That is, "performance (P) is a function of the sensory modality of signals (M), the salience of signals (S), stimulus uncertainty (U), the characteristics of the background of nonsignal events in which critical signals for detection are embedded (B), and task complexity (C)" (Huey & Wickens, 1993, p. 142). Table 1 lists some of the key findings related to the five types of variables included in the functional equation.

Table 1
Effects of Signal Modality, Signal Salience, Stimulus Uncertainty, Background Event Context, and Stimulus Complexity on Vigilance Performance

COMPONENT OF VIGILANCE	EFFECT ON VIGILANCE PERFORMANCE
Signal Modality	Auditory vigilance tasks are more efficient and stable over time than visual or cutaneous vigilance tasks. Techniques are available to enhance performance with visual signals (*e.g.,* redundant displays that present signals simultaneously in both the visual and auditory modes).
Signal Salience	Under conditions of sustained attention, stimulus amplitude enhances performance and increases stability of performance. Increasing signal duration also increases salience.
Stimulus Uncertainty	Temporal uncertainty (*when* signals will appear) and spatial uncertainty (*where* signals will appear) both degrade performance. Speed and accuracy of detection is greater when signals occur regularly and when signals occur frequently.

NOTE: Based on Huey and Wickens (1993) and Moroney (1995). Appendix B lists the sources used by Huey and Wickens (1993), and by Moroney (1995), to reach the conclusions presented in Table 1.

Table 1 (continued)
Effects of Signal Modality, Signal Salience, Stimulus Uncertainty, Background Event Context, and Stimulus Complexity on Vigilance Performance

COMPONENT OF VIGILANCE	EFFECT ON VIGILANCE PERFORMANCE
Background Event Context	Monitoring against a background of irregular (asynchronous) events is poor compared to monitoring against a background of regular events. Background event rate moderates other variables in the functional equation, and has led researchers to believe that background event rate "is probably the prepotent psychophysical factor in vigilance performance" (Huey and Wickens, 1993, p. 145).
Stimulus Complexity	Experimental vigilance studies typically use relatively "simple" tasks involving perceptual discriminations. Efforts to study the consequences of increased task complexity have produced mixed results.

Application of the vigilance findings associated with the psychophysical equation in the context of the AHS is not a simple task. However, it seems reasonable to suggest that the findings concerning background event context and stimulus uncertainty may be the most relevant to a consideration of the driver's role in the AHS. The findings about signal modality and signal salience may be more relevant to display design issues than to the issue at hand. The findings about stimulus complexity should probably be considered in conjunction with the findings about vigilance derived from studies conducted in operational environments (see Section 3.2.6).

3.2.4 Impact of Environmental Stress

The concept of *stress* is difficult to define. In reviewing the impact of environmental stress on vigilance performance, Huey and Wickens (1993, p. 148) indicate that stress "is considered to be any threat to the physical or psychological well-being of the organism (Wingate, 1972)." As shown in Table 2, Huey and Wickens (1993) describe the effects of four types of environmental stress: (1) temperature, (2) noise, (3) vibration, and (4) loss of sleep. Consideration of these four types of stress in the context of the AHS suggests that the most likely to affect a driver's performance is the loss of sleep.

Table 2
Effects of Environmental Stress (Temperature, Noise, Vibration, and Loss of Sleep) on Vigilance Performance

STRESSOR	EFFECT ON VIGILANCE PERFORMANCE
Temperature	Excessive heat or cold that disturbs core body temperature impairs vigilance performance.
Noise	Noise has little effect when monitoring a single stimulus. With multiple stimuli, intermittent noise results in conflicting effects; continuous loud noise (> 90dB SPL) degrades performance when task resource or information processing demands are high but not when task demands are low; low levels of noise (c. 64 dB SPL) can enhance performance under low levels of task demand.
Vibration	Vibration has little effect except when it is sufficient to blur vision.
Loss of Sleep	Alteration of normal sleep schedule impairs vigilance performance.

NOTE: Based on Huey and Wickens (1993). Appendix C lists the sources used by Huey and Wickens (1993) to reach the conclusions presented in Table 2.

3.2.5 Criticisms of Traditional Experimental Vigilance Research

Critics of vigilance research direct attention to the fact that despite more than 40 years of effort, "vigilance research has not had a palpable impact on real-world systems" (Wiener, 1987, p. 725). As shown in Table 3, these critics focus on a variety of issues.

Table 3
Criticisms of Vigilance Research

ISSUE	SOURCES
Few real world decrements in vigilance	Adams, 1963, 1987; Elliott, 1960; Kibler, 1965; Nachreiner, 1977; Smith & Lucaccini, 1969; Teichner, 1974.
Imperfection in the task/unreality of the laboratory situation	Chapanis, 1967; Craig, 1984; Jerison & Pickett, 1964; Kibler, 1965; Mackie, 1984; Nachreiner, 1977; Wiener, 1984.
Selection of independent variables	Craig, 1984; Kibler, 1965; Mackie, 1984; Nachreiner, 1977; Wiener, 1984.
Deficiencies in training researchers	Mackie, 1984.
Confounding of signal probability and event rate	Moroney, 1995.

NOTE: Based on Adams (1987), Moroney (1995), and Wiener (1987).

Despite the challenges of applying the results of vigilance research, Wiener (1987) and Adams (1987) agree that the quality of the basic vigilance research has been good. As Wiener (1987, p. 735) concluded, "(1) well-designed systems taking into account the role of the human monitor—rare; (2) outlook for future systems doing better—medium; (3) research to date—well done."

3.2.6 Vigilance in Operational Environments

The amount of vigilance research conducted using simulated and operational tasks is very small when compared with that conducted in laboratories, and the results have not consistently demonstrated the vigilance decrement found in laboratory studies (Parasuraman, 1986). Some sonar/radar monitoring and surveillance studies indicate a vigilance decrement (Baker, 1962; Colquhoun, 1967, 1977; Schmidke, 1966, 1976; Solandt & Partridge, 1946, cited in Parasuraman, 1986); others indicate unacceptably low levels of performance on the operational vigilance task (Baker, 1967; Hermann, 1977; Japenga, 1982; Tickner & Poulton, 1973, cited in Parasuraman, 1986). Industrial inspection studies show that "inspectors generally make more omission errors [false negatives] than commission errors (false alarms) (Parasuraman, 1986, p. 43-29).

In light of the inconsistent findings in vigilance studies conducted in operational environments, Parasuraman (1986) suggests that in the real world the issue is not the presence or absence of the vigilance decrement, but the *interaction* between any vigilance decrement and the minimum level of acceptable task performance (vigilance efficiency). This interaction can take several forms:

- Acceptable Vigilance Efficiency (*i.e.* task performance meets, or exceeds, minimum level for acceptance)
  - — No vigilance decrement
  - — Any vigilance decrement is operationally *insignificant*
- Unacceptable Vigilance Efficiency (*i.e.,* task performance does not meet minimum level for acceptance)
  - — No vigilance decrement
  - — Any vigilance decrement is operationally *insignificant*
  - — Any vigilance decrement is operationally significant
    (NOTE: This type of scenario is implicit in many, perhaps most, experimental vigilance studies.)

This interaction seems pertinent to the consideration of the driver's role in the AHS for it helps to clarify the role of vigilance in this environment. It changes the focus from vigilance performance *per se*, to vigilance efficiency (*i.e.,* to the minimum acceptable level of operational task performance). This change in focus underscores the idea that the key issue is not the presence or absence of a vigilance decrement, but of the impact of any decrement on the acceptability of operational task performance.

3.3 Automation in Other Complex Systems

> *The question today is not whether a function can be automated, but whether it should be. . . . It is highly questionable whether total system safety is always enhanced by allocating functions to automatic devices rather than human operators*
>
> (Wiener & Curry, 1980, p. 995)

> *Human supervisory control, then, is a natural complement to automation, although this fundamental fact is not well appreciated and understood.*
>
> (Sheridan, 1996, p. 450)

According to Hancock and Parasuraman (1992), efforts to develop Intelligent Vehicle-Highway Systems (IVHS) can, and should, incorporate insights gained from experience with high levels of automation in other transportation systems (*e.g.*, aviation, air traffic control, and shipping). These issues include, but are not limited to:

- Mental workload regulation (see Verwey, 1990 for a description of one effort to achieve this goal)
- Management of the *driver-in-the-loop* problem
- Automation induced complacency
- Skill degradation
- Tradeoffs between false positives and false negatives in collision avoidance
- Interface design for drivers with widely varying abilities and capabilities

In discussing these five issues, Hancock and Parasuraman (1992) note that operators of other highly automated transportation systems differ substantially in terms of selection and training from drivers on the nation's highways.[5] Hancock, Dewing, and Parasuraman (1993) describe these differences in more detail and direct attention to differences not only in selection and training, but also in age, motivation, and level of expertise. Consideration of these issues directs attention to a number of basic human factors issues including the role of humans in highly automated systems, and concepts related to mental workload and situation awareness.

3.3.1 What Is the Role of the Human Operator in Human-Machine Systems?

> *Contrary to the implication of the term* automated, *humans have remained a critical part of most automated systems. They must monitor for failures of the automated system and the presence of conditions the system is not designed to handle. . . . Because the systems to be monitored continue to increase in complexity with the addition of automation, an increased trend toward failures often accompanies the incorporation of automation (Wickens, 1992; Wiener, 1985). . . . In examining these failures, it becomes apparent that the coupling of human and machine in the form of observer and performer is far from perfect in terms of optimizing the overall functioning of the joint human-machine system.*
>
> *(Endsley, 1996, pp. 163-164)*

The widespread introduction of high levels of automation in various environments has led to profound changes in the role of the human—from the actor engaged in performing tasks, to

[5] Other listings of human factors issues associated with IVHS can be found in Hancock and Caird (1992a, 1992b), Hancock, Dewing, and Parasuraman (1993), and Hancock, Parasuraman, and Byrne (1996).

the supervisor engaged in monitoring the automated systems and intervening when necessary (Endsley, 1996). Beginning in the 1960s, the generally accepted advice concerning the role of the human in automated systems was "that machines will run themselves and human monitors will keep watch and intervene when necessary" (Wiener, 1987, p. 731).

In the 1980s, there were some dramatic failures in highly automated systems (*e.g.,* nuclear power plant accidents at Three Mile Island and Chernobyl, and catastrophic crashes of commercial airliners) in which "human monitors reacted either too late, incorrectly, or not at all" (Wiener, 1987, p. 732). These events challenged traditional practices and forced a reconsideration of the role of the human in highly automated systems. They also contributed to the awareness that "the role of the human monitor in future systems in not simply a question of resource allocations (Price, 1985) but of something far more basic: the very nature of the human machine ensemble" (Wiener, 1987, p. 734).

More recently, some investigators have begun to advocate a middle ground—*adaptive automation*—between traditional roles and responsibilities as actors in a situation, and evolving roles and responsibilities as monitors/supervisors of a situation. In the former role, the human activities were often physical (*i.e.,* overtly doing something); in the latter role, the human activities may depend primarily on perception and information processing (Endsley, 1996). Experience in highly automated systems has shown that situation awareness, mental workload, and the ability to resume manual control when necessary may be adversely affected. (Parasuraman & Bahri, 1992). According to Parasuraman, Hilburn, Molloy, & Singh (1991), design guidelines concerning adaptive automation are very tentative, and empirical research to support this position is very limited. Nevertheless, the concept is central to European efforts to develop Generic Intelligent Driver Support (GIDS) systems ("intelligent co-driver systems") that are designed to "adapt to the momentary workload of the driver" (Verwey, 1990, p. 7).

3.3.2 Two Key Issues: Mental Workload and Situation Awareness

Much research concerning mental workload and situation awareness has been conducted in the cockpit environment. However, this work can also be used to characterize phenomena in other highly automated environments (*e.g.,* process control, air traffic control, and nuclear power plant operations).

The term *mental workload* is used to characterize the operator's experience of "the interaction between the requirements of a task, the circumstances under which it is performed, and the skills, behaviors, and perceptions of the operator" (Braby, Muir, & Harris, 1991, p. 36). The term *situation awareness* emphasizes the importance of the context in which a task is performed. As a description of a phenomenon, *situation awareness* "draws attention to the intimate interactions between human and environment in determining meaning (or what matters) and reflects an increased appreciation for the intimate coupling between processing stages (*e.g.,* perception, decision, and action) within closed-loop systems" (Flach, 1995, p. 149).[6]

3.3.2.1 Mental Workload. According to Barber (1988), much of the early research concerning mental workload was done in conjunction with studies of the skills needed to fly an airplane. However, automation is changing the nature of the pilot's tasks. That is, manual control activities are decreasing, and monitoring activities with essential perceptual and cognitive components are increasing.

[6] It should be noted that this descriptive conception of situation awareness represents one approach to the issue of situation awareness. A second approach to situation awareness views it as a *causal* agent. However, Flach (1995) cautions that "SA [situation awareness] as a causal explanation does not lead to testable hypotheses but only to circular arguments" (p. 155).

Two terms are often used in conjunction with discussions of mental workload: (1) overload and (2) underload. Mental overload "occurs when an operator is called to perform beyond the limits of his or her resources" (Barber, 1988, p. 101). It has been investigated using a variety of approaches including primary-task measures, secondary-task measures, physiological measures, and subjective measures. (See Barber, 1988, Ch. 5 for a review of studies conducted using each of these approaches). Intuitively, the term underload would seem to be the reverse of overload, and it is sometimes described in terms of boredom and complacency (Braby, Muir, & Harris, 1991). However, according to Braby, Muir, and Harris (1991, p. 36) "it cannot be assumed that all existing workload techniques are suited to the operator states that reflect flight crew underload. Thus the need to develop a working concept of underload and techniques to assess this type of workload is becoming the focus of attention."

The classic laboratory vigilance scenario—one that requires attention, but provides little information—has been viewed as likely to result in underload (Braby, Muir, & Harris, 1991; Warm, Dember, & Hancock, 1996). However, recent research has begun to re-examine the effects of laboratory types of vigilance tasks on the human operator (Rehmann, 1995).

According to Warm, Dember, Gluckman, and Hancock (1991), the mental cost of vigilance task performance is considerable, and transitions in workload—from high to low, or from low to high—can result in human performance decrements. Using a subjective workload rating technique developed in the aviation environment (the NASA-TLX subjective workload rating scale), Warm and his colleagues performed a series of experiments to assess whether factors known to degrade performance on vigilance tasks (*e.g.,* signal salience, event rate, spatial uncertainty, display uncertainty, noise) increased mental workload ratings. These experiments are reviewed in a chapter entitled *Vigilance and Workload in Automated Systems* (Warm, Dember & Hancock, 1996). The results show that contrary to previous belief, "vigilance tasks are *not quintessential examples of task underload.* Instead, *the cost of mental operations in vigilance is substantial,* and mental demand and frustration tend to be the primary contributors to workload" (p. 186).

3.3.2.2 Situation Awareness.

> *Situation awareness (SA), a person's mental model of the world around him or her, is central to effective decision making and control in dynamic systems.*
>
> *(Endsley, 1996, p. 165)*

The term *situation awareness* was originally used to describe the pilot's experience of being able to make sense of a situation and to act decisively and effectively (high situation awareness), or of being confused, lost, or unable to understand a situation (low situation awareness) (Flach, 1996). Today, the term is used to help characterize the operator's experience in a variety of complex operational domains (*e.g.,* nuclear power plant operation, air traffic control, or process control) (Endsley, 1996).

Situation awareness incorporates three key elements: (1) perception, or Level 1 SA, (2) comprehension/understanding, or Level 2 SA, and (3) decision-making/action, or Level 3 SA, and it is the higher levels of SA that allow human operators to make decisions and to take actions in a timely manner. (Endsley, 1996). The term situation awareness emphasizes the importance of context and of the human operator's ability to comprehend the meaning of what is perceived. It also underscores the idea that perception of a signal, or a piece of information, is important, but it is not sufficient to ensure appropriate decision-making and action.

Experience with automation in a variety of environments has shown that automation can impact situation awareness and contribute to the *human-in-the-loop* performance problem. The essence of this problem is that when humans serve as monitors, they may be slow to detect problems. They may need additional time to understand the situation and to determine an appropriate course of action (Endsley, 1996). The pilot's experience with this problem is vividly described by McDaniel.

> If the automation of a critical function is not perfectly reliable, the pilot will need to monitor it in order to intervene quickly should a malfunction occur. If the pilot continuously monitors the automation, he or she can intervene in about one second. If the pilot is attending to another task when the malfunction occurs, the reaction time will be several seconds because he or she must also refresh his or her awareness of the situation as well as detect that a malfunction has occurred, what has malfunctioned, and what to do about it. In many situations, the malfunctioning aircraft cannot survive even those few seconds. As a result, a pilot dares not perform a second noncritical task rather than monitor the automated critical task. So, while this type of automation permits a useful task to be accomplished, it does nothing to free the pilot's attention resources for other tasks. (McDaniel, 1988, p. 837, quoted in Hancock & Parasuraman, 1992, p. 186)

Automation does not have to have a negative impact on situation awareness. However, Endsley (1996) has identified several mechanisms by which automation can have a negative impact including:

- Automation may increase the operator's mental workload.
- The operator may neglect to monitor automation due to complacency, or over-reliance, on the automation.
- The operator may fail to monitor automation successfully because of vigilance problems.
- High false alarm rates may lead to a lack of trust in the automation, a tendency to ignore alarms, or an inability to detect alarms if they have been disabled.
- Assumption of a passive rather than an active role in system control may contribute to inferior information processing (Cowan, 1988; Slamecka & Graf, 1978, cited in Endsley, 1996).
- Elimination of feedback, or changes in the type of feedback, can leave people "out-of-the loop."
- The operators may not understand the automation they are using due to factors such as the complexity of the system, poor interface design, or lack of adequate training.

3.4 Driving Performance and Vigilance, Mental Workload, and Situation Awareness

Studies of driving performance and vigilance, mental workload, or situation awareness are not frequent. Nevertheless, the result of a few such studies can provide useful insights into the relevance of these concepts when determining the driver's role in the Automated Highway System.

Brown, Simmonds, and Tickner (1967) investigated control skills, vigilance, and secondary task performance during 12 hours of continuous driving on actual roadways. The vigilance task

> required the detection of a light signal which was presented through an aperture in the backing of the interior and wing mirrors of the car. The signal was of low intensity and could be seen only by fixating within the area of a mirror. All 3 lamps were switched on simultaneously and the subject had to call out when he saw them. His response time was measured to the nearest 0.2 sec. The mean inter-signal interval was 10 min (range 3 to 17 min) and undetected signals were switched off after 60 sec. (p. 666)

Using a total of 8 subjects (male drivers, age 30-46, with 5-28 years of driving experience) reaction time varied from 6.0 to 6.5 seconds in the morning, and from 4.5 to 5 seconds in the afternoon. In addition, performance variability on the secondary task was reliably higher during 12 hours of almost continuous driving than during 12 hours of sedentary work with intermittent driving. Driving control skills were not reliably different under either of the two conditions.

In another study, Brown and Poulton (1961) concluded "that the subsidiary [secondary] task technique can be used effectively in field studies to measure the spare mental capacity of the driver" (p. 39). However, in a review of driving literature that used a secondary task research paradigm, Noy (1987) concluded that:

> many of the studies involving secondary task techniques lack a valid theoretical basis for the application of the technique or the particular choice of secondary task. Moreover, very few of these studies have examined mutual interference between secondary tasks and driving to investigate the nature of the interaction and underlying factors. However, the fact that some studies have reported interference is sufficient to establish that in-vehicle tasks may complete with driving. (p. 206).[7]

A recent study by Endsley and Kiris (1995, cited by Endsley, 1996) indicates the complexity of the relationships between vigilance, monitoring, and situation awareness. They found "that subjects' situation awareness was lower under fully automated and semi-automated conditions than under manual performance in an automobile navigation task" (Endsley, 1996, p. 168). They also concluded that "turning a human operator from a performer into an observer can, in and of itself, negatively affect situation awareness, even if the operator is able to function as an effective monitor, and this can lead to significant problems in taking over during automation failure" (Endsley, 1996, p. 168).

4. CONCLUSIONS

The determination of the human role in any highly automated system is complex. Determination of the human role in the Automated Highway System is likely to be especially complex. Reasons for this complexity are many, but certainly include the diversity of the user population, the issue of vigilance, the interaction between vigilance and operational task performance, and the impact of automation on the nature of the driver's task, mental workload, and situation awareness.

Arguments to support increased automation and transformation of the driver's role to include more monitoring and vigilance tasks can be based on the anticipated benefits of increased automation—benefits generally focus on improved highway safety and increased highway

[7] The issue of secondary task selection in studies of driver mental workload, is addressed in more detail by Verwey (1990).

capacity. The arguments against such a transformation of the driver's role can be based on information from several types of sources:

- Data about basic human capacities (*e.g.*, reaction time) within the driving population
- Data about human performance on vigilance tasks in experimental and operational environments.
- Insights from experience with high levels of automation in other complex human-machine systems.

Information from these three types of sources leads to four conclusions.

- **The diverse user population for the Automated Highway System will offer system designers challenges that may not have been encountered in other highly automated systems.**

    These challenges include, but are not limited, to extensive variation in physical, perceptual and cognitive abilities; in age, health, training; and in driving knowledge, skill, and expertise.

- **Operator vigilance is likely to be an issue; however, the issue is far more complex than might appear from the results of classic laboratory vigilance studies.**

    It is clear from classic laboratory experiments in vigilance that humans are not well suited for monitoring infrequent signals, and there is emerging evidence that the mental workload associated with vigilance tasks is not negligible. However, in operational settings, the situation is much more complex. Vigilance performance will interact with basic task performance, and may prove to be insignificant if basic task performance is unacceptable.

- **Regulation of mental workload and workload transitions, and assurance of adequate situation awareness to ensure that operators can intervene when necessary are likely to be major design issues.**

    Experience in other highly automated environments has taught many lessons about the problems that occur when mental workload is excessive, or when situation awareness is inadequate. The existence of these problems with highly selected and trained users of existing systems suggests that these issues may be of even greater concern in the Automated Highway System.

- **The *human-in-the-loop* performance problem that has been observed in other highly-automated environments must be considered to ensure that automation does not leave the driver unable to assume control when needed.**

    The task of determining the human role in the Automated Highway System will require the innovative use of information and insights from many domains of human factors. Vigilance performance is certainly one concern. Lessons learned from high levels of automation in other operational environments are a second concern. And, these issues must be addressed in a manner that honors the diversity of the user population.

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6. ADDITIONAL READINGS

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APPENDIX A

Immediate access to a wealth of potentially useful information can be obtained from the World Wide Web sites listed in Table A1. They provide information and links to information related to the Automated Highway System and to human factors issues in automation.

Table A1
Internet Resources

Title of Web Site	HTTP:// Address
AspectOne Launch Site	http://www.wcinet.net/~aspect/
Aviation Operations Branch, NASA-AMES	http://olias.arc.nasa.gov/
Aviation Operations Branch: Publications	http://olias.arc.nasa.gov/publications/reference-publications.html
Bluecoat (Europe)	http://bluecoat.eurocontrol.fr/
Cognitive Psychophysiology Lab, Naval Health Research Center	http://labhsp.nhrc.navy.mil/
Department of Transportation	http://web.fie.com/fedix/dot.html
ErgoWeb, Inc.	http://www.ergoweb.com/Pub/ewhome.shtml
FAA Office of Aviation Research	http://www.faa.gov/aar/aarhome.htm
Federal Highway Administration	http://web.fie.com/htdoc/fed/dot/fha/any/menu/any/fhaindex.htm
Human Factors and Ergonomics Society.	http://www.hfes.org/
Human Performance Technologies	http://ott.sc.ist.ucf.edu/2_1/index.htm
Human-Centered Transportation Systems	http://www.hf.faa.gov:80/nstc/brochure.htm
Institute of Transportation Engineers	http://www.ite.org/
ITS Online	http://www.itsonline.com/
National Highway Traffic Safety Administration	http://www.nhtsa.dot.gov/
National Transportation Library, Bureau of Transportation Statistics	http://www.bts.gov/smart/smart.html
The Aerospace Navigator	http://www.ultranet.com/~adjm/aero/aeronav.html
The California PATH Database	http://sunsite.berkeley.edu/~path/index.html
The Turner Fairbank Highway Research Center	http://www.tfhrc.gov/
SAE Global Mobility Database	http://www.sae.org/GMD/
Transportation Research Board	http://www.nas.edu/trb/index.html
Transportation Research Board Bookstore	http://www2.nas.edu/trbbooks/
Virginia Tech Center for Transportation Research	http://www.ctr.vt.edu/

APPENDIX B

Table B1
Sources Used to Summarize the Effects of Signal Modality, Signal Salience, Stimulus Uncertainty, Background Event Context, and Stimulus Complexity on Vigilance Performance

COMPONENT OF VIGILANCE	EFFECT ON VIGILANCE PERFORMANCE	SOURCES
Signal Modality	Auditory vigilance tasks are more efficient and stable over time than visual or cutaneous vigilance tasks. Techniques are available to enhance performance with visual signals (*e.g.*, redundant displays that present signals simultaneously in both the visual and auditory modes).	Craig, Colquhoun, Corcoran, 1976; Davies & Parasuraman, 1982; Doll & Hanna, 1989; Galinsky, Warm, Dember, Weiler, & Scerbo, 1990; Hatfield & Loeb, 1968; Loeb & Binford, 1968; Parasuraman & Davies, 1977; Warm & Jerison, 1984.
Signal Salience	Under conditions of sustained attention, stimulus amplitude enhances performance and increases stability of performance. Increasing signal duration also increases salience.	Adams, 1956; Corcoran, Mullin, Rainey, & Frith, 1977; Dember & Warm, 1979; Guralnick, 1972; Kelley, 1969; Loeb & Binford, 1963; Metzger, Warm, & Senter, 1974; Thurmond, Binford, & Loeb, 1970; Warm, Loeb, & Alluisi, 1970; Wiener, 1964; Wiener, 1973.
Stimulus Uncertainty	Temporal uncertainty (when signals will appear) and spatial uncertainty (where signals will appear) both degrade performance. Speed and accuracy of detection is greater when signals occur regularly and when signals occur frequently.	Adams & Boulter, 1964; Alluisi, 1966; Baddeley & Colquhoun, 1969; Colquhoun & Baddeley, 1964; Colquhoun & Baddeley, 1967; Griffin, Dember, & Warm, 1986; Jenkins, 1958; Joshi, Dember, Warm, & Scerbo 1985; Krulewitz & Warm, 1977; Mackworth, 1961/1950; McFarland & Halcomb, 1970; Milosevic, 1974; Nicely & Miller, 1957; See, Simon, Warm, Dember, & Fowler, 1995; Smith, Warm, & Alluisi, 1966; Sullivan 1991; Warm, & Alluisi, 1971; Warm & Jerison, 1984; Warm, Dember, Murphy, & Dittmar, 1992; Williges, 1971; Warm, Eppe, & Ferguson, 1974.

NOTE: Based on Huey and Wickens (1993) and Moroney (1995).

Table B1 (continued)
Sources Used to Summarize the Effects of Signal Modality, Signal Salience, Stimulus Uncertainty, Background Event Context, and Stimulus Complexity on Vigilance Performance

COMPONENT OF VIGILANCE	EFFECT ON VIGILANCE PERFORMANCE	SOURCES
Background Event Context	Monitoring against a background of irregular (asynchronous) events is poor compared to monitoring against a background of regular events. Background event rate moderates other variables in the functional equation, and has led researchers to believe that background event rate "is probably the prepotent psychophysical factor in vigilance performance" (Huey and Wickens, 1993, p. 145).	Bowers, 1983; Jerison & Pickett, 1964; Krulewitz & Warm, 1977; Krulewitz, Warm, & Wohl, 1975; Lanzetta, Dember, Warm, & Berch, 1987; Loeb & Binford, 1968; Mackworth, 1968; Mackworth, 1969; Metzger, Warm, & Senter, 1974; Moore & Gross, 1973; Parasuraman, & Davies, 1976; Parasuraman, 1979; Parasuraman, 1985; Parasuraman, Warm, & Dember, 1987; Richter, Senter, & Warm, 1981; Scerbo, Warm, Doettling, Parasuraman, & Fisk, 1987; Scerbo, Warm, & Fisk, 1987; Taub & Osborne, 1968; Warm & Berch, 1985; Warm & Jerison, 1984.
Stimulus Complexity	Experimental vigilance studies typically use relatively "simple" tasks involving perceptual discriminations. Efforts to study the consequences of increased task complexity have produced mixed results.	Adams & Humes, 1963; Adams, Humes, & Sieveking, 1963; Craig, 1991; Dember, Warm, Bowers, & Lanzetta, 1984; Fisk & Schneider, 1981; Hancock, 1984; Jerison, 1963; Loeb, Noonan, Ash, & Holding, 1987; Lysaght, Warm, Dember, & Loeb, 1984; Montague, Weber, & Adams, 1965; Schneider & Shiffrin, 1977; Warm, Howe, Fishbein, Dember, & Sprague, 1984.

APPENDIX C

Table C1
Sources Used to Summarize the Effects of Environmental Stress on Vigilance Performance Effects of Environmental Stress (Temperature, Noise, Vibration, and Loss of Sleep) on Vigilance Performance

STRESSOR	EFFECT ON VIGILANCE PERFORMANCE	SOURCES
Temperature	Excessive heat or cold that disturbs core body temperature impairs vigilance performance.	Bell, Provins, & Hiorns, 1964; Benor & Shvartz, 1971; Colquhoun & Goldman, 1972; Hancock, 1984; Hancock, 1986; Kerslake & Poulton, 1965; Mackie & O'Hanlon, 1977; Mackworth, 1948; Mackworth, 1961/1950; Pepler, 1953; Poulton & Edwards, 1974; Poulton, Edwards, & Colquhoun, 1974; Wilkinson, Fox, Goldsmith, Hampton, & Lewis, 1964.
Noise	Noise has little effect when monitoring a single stimulus. With multiple stimuli, intermittent noise results in conflicting effects; continuous loud noise (> 90dB SPL) degrades performance when task resource or information processing demands are high but not when task demands are low; low levels of noise (c. 64 dB SPL) can enhance performance under low levels of task demand.	Blackwell & Belt, 1971; Broadbent, 1954; Broadbent & Gregory, 1965; Davies & Hockey, 1966; Easterbrook, 1959; Hancock, 1984; Hancock & Warm, 1989; Hartley & Shirley, 1977; Hockey, 1970; Jerison, 1959a; Jones, 1983; Jones, 1984; Koelega & Brinkman, 1986; Loeb, 1986; Poulton, 1977; Poulton & Edwards, 1974.
Vibration	Vibration has little effect except when it is sufficient to blur vision	Goether, 1971; Hancock, 1984; Poulton, 1977; Shoenberger, 1967; Schohan, Rawson, & Soliday, 1965; Weisz, Goddard, & Allen, 1965; Wilkinson & Gray, 1974;

NOTE: Based on Huey and Wickens (1993).

Table C1 (continued)
Sources Used to Summarize the Effects of Environmental Stress on Vigilance Performance
Effects of Environmental Stress (Temperature, Noise, Vibration, and Loss of Sleep) on Vigilance Performance

STRESSOR	EFFECT ON VIGILANCE PERFORMANCE	SOURCES
Loss of Sleep	Alteration of normal sleep schedule impairs vigilance performance.	Anch, Brownian, Mitler, & Walsh, 1988; Bergstrom, Gillsberg, & Arnberg, 1973; Broadbent, 1963; Colquhoun, 1972; Davies & Parasuraman, 1982; Hartley, 1974; Hockey, 1986; Horne, Anderson, & Wilkinson, 1983; Johnson & Naitoh, 1974; Rosa, Bonnet, & Warm, 1983; Rosekind, Gander, & Dinges, 1991; Seidel, Roth, Roehrs, Zorick, & Dement, 1984; Taub & Berger, 1973; Webb & Agnew, 1974; Wilkinson, 1968; Wilkinson, Edwards, & Haines, 1966; Williams, Kearny, & Lubin, 1965.